Cryostat Options for Constellation-X

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7 February, 2002

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Executive Summary

The baseline cooling system for the planned micro-calorimeter of the Spectroscopy X-Ray Telescope (SXT) on Constellation-X consists of a multistage continuous adiabatic demagnetization refrigerator (ADR), operating between 0.050 K and ~6 K, and a 6 K version of Creare's turbo-Brayton cryocooler. The development path to a 6 K cryocooler remains uncertain and presents a major risk to Constellation-X. Further risk resides in the research and development of the warmer stages of the ADR.

The effort reported here was an attempt to identify a cooling solution with less technological risk that would also fall within the current mass and volume constraints. Four system options were examined ranging from one similar to the X-Ray Spectrometer (XRS) of Astro-E, to the above mentioned cryocooler system. In fact, the XRS cryostat was used as a prototype from which three stored cryogen options were directly scaled.

It must be remembered, that even though stored cryogen systems of several types have been employed in the past, and are considered "existing technology", each new application presents unique uncertainties and risks.

In what follows, consideration is given only to the Transition Edge Sensor (TES) detector system. This is not a choice between technologies but a choice of starting point. Configurations built around a Neutron-Transmutation-Doped semiconductor (NTD) detector system will be considered in the near future.

We began by directly scaling the superfluid-helium/solid-neon (SfHe/SNe) cryostat of XRS for the colder Constellation-X environment (Option 1). We then modified that design by incorporating an off-the-shelf 35 K pulse tube cryocooler to actively cool a shield surrounding the solid neon guard (Option 2a) and further modified that option by replacing the solid neon with solid hydrogen (Option 2b). Finally we developed a configuration for the baseline cryocooler solution (Option 3).

The cryostat of Option 1 has proven to be far too large and massive to be considered for a 6 year lifetime. The cryostat of Option 2b gets closer to the 100 kg mass allocation, but is still too large to fit on the detector bench, while the equally massive cryostat of Option 2a does just fit within the sunshade envelope. The best of these options, Option 2a, remains approximately 50 kg, or 100 kg per launch, over budget. Note that these designs are based on a 110 K main shell temperature and any reduction in that temperature would have beneficial effects on each option. The all-cryogen system of Option 1 would benefit the most by a still colder shell, but would never get light enough or small enough to meet requirements. The cryogen needs of Options 2 would change little, the desirable effects being manifest mostly in lower power requirements from the cryocoolers. Regardless, even a shortened mission won't bring Options 1 and 2 into compliance.

The Option 3 cryostat remains the only one to meet both mass and volume constraints. However, all cryostats protrude into the bench as it is currently configured – least so for Option 3. A summary of all results can be found in Table 1 below.

The next step in this process is to do a more detailed design of the external support structure so that it and the main shell can be incorporated into the spacecraft thermal model. From that, more accurate determination can be made of the main shell temperature and that then iterated into the above designs.

System/ Option	Cooling Method	Primary Cryogen (ADR Sink)	Secondary Cryogen	Lifetime (years)	Shell Size Ø x L (mm)	Total Mass (kg)	Comments
XRS	Stored Cryogen	SfHe	SNe	2.5	1025 x 1172	396	230 K main shell temperature
Option 1	Stored Cryogen	SfHe	SNe	6	940 x 994	228	Direct scaling of XRS cryostat for 110K main shell temperature. Too large and too massive.
Option 2a	Hybrid	SfHe	SNe	6	740 x 938	155	Incorporates an off-the-shelf pulse tube cryocooler to cool an inner guard shield to 35 K. Feasible with current technology. Fits current architecture but more massive than current budget.
	Hybrid	SfHe	SNe	4	711 x 809	128	
	Hybrid	SfHe	SNe	2	690 x 664	106	
Option 2b	Hybrid	SfHe	SH_2	6	900 x 908	150	A wash in mass with Option 2a but larger. Does not meet current size or mass constraints.
Option 3	Turbo-Brayton Cooler	N/A	N/A	Indefinite	620 x 733	99	Baseline, but has the greatest technological risk. Meets size and mass constraints.

Table 1 Cryostat scaling summary.

Cryostat Options for Constellation-X

1.0 Introduction: The baseline cooling system for the planned micro-calorimeter of the Spectroscopy X-Ray Telescope (SXT) on Constellation-X consists of a multistage continuous adiabatic demagnetization refrigerator (ADR), operating between 0.050 K and ~6 K, and a 6 K version of Creare's turbo-Brayton cryocooler. The development path to a 6 K cryocooler has had its ups and downs and the uncertainty that remains presents a major risk to Constellation-X.

This paper describes the results of an effort to identify a cooling solution with less technological risk. Such a goal limits us to certain stored cryogen systems and ADRs with sink temperatures near 1.3 K. Enough risk remains in the research and development of still warmer ADR stages to obviate their use in this effort. It must always be remembered, that even though stored cryogen systems can be considered "existing technology", each new application presents unique, though acceptable, uncertainties and risks.

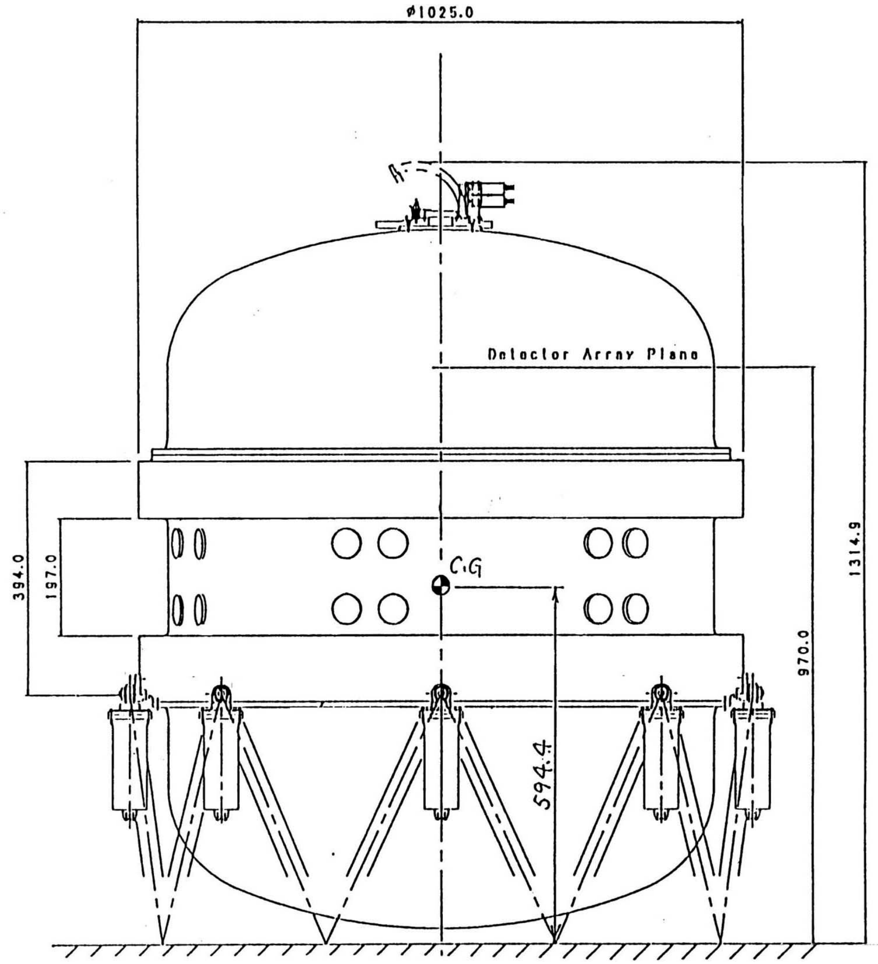
Four system options were examined ranging from one similar to the X-Ray Spectrometer (XRS) of Astro-E, to the above mentioned cryocooler system. In fact, the XRS system was used as a prototype from which three stored cryogen options were directly scaled.

1.1 XRS as prototype: The X-Ray Spectrometer (XRS) onboard the ill-fated Astro-E observatory was a precursor instrument for the planned micro-calorimeter of Constellation-X. Major components of the XRS cryostat are depicted in Figure 1. The low temperature required by the detector was produced by a single stage ADR operating between 0.065 K and 1.3 K. The 1.3 K primary heat sink was provided by 20 liters (usable volume) of superfluid helium. The helium tank was suspended by graphite/epoxy straps from the secondary, or guard, cryogen tank containing 120 liters of solid neon at ~17 K. The neon tank, in turn, was suspended from the ~230 K main vacuum shell by low-conductivity straps. Distributed between the main shell and the neon tank were three vapor-cooled shields. The system was designed for a minimum 2 year mission with a goal of 2.5 years. The total heat load on the helium tank was less than 800 μW and was based on a dewar main shell temperature of 230 K.

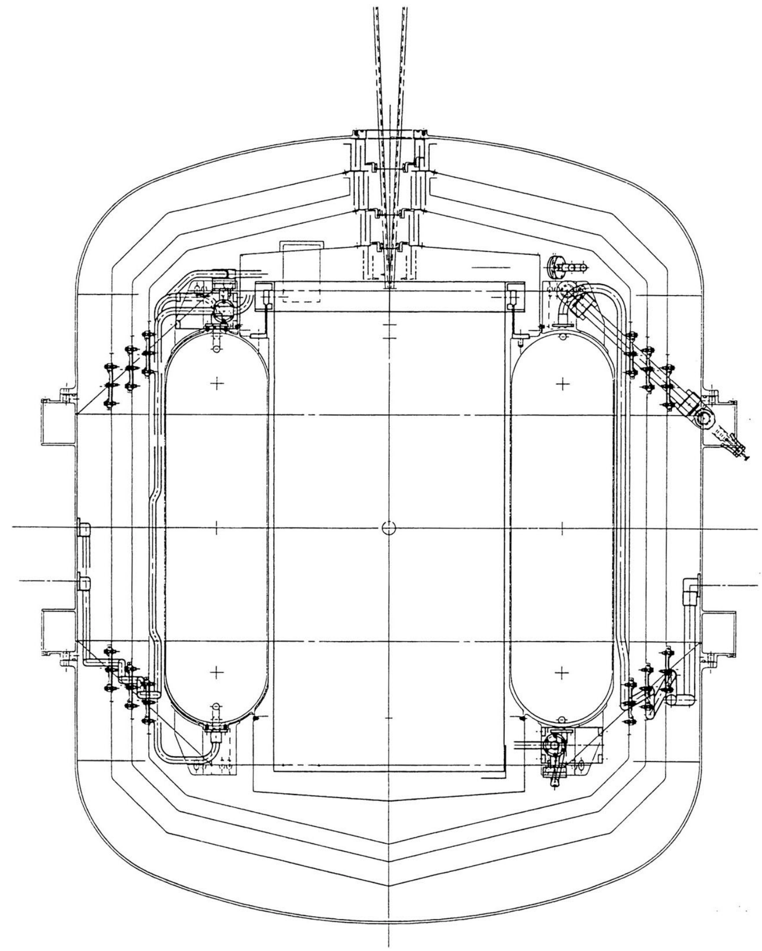
XRS was given rather a rough ride on a Japanese M-5 expendable launch vehicle. Static design loads were in the neighborhood of 35 g axial and 15 g lateral. The mass properties of the cryostat are given below in Table 2.

Element	Mass (kg)
Cryostat main shell	65.8
Neon tank	34.2
Vapor cooled shields (3) and MLI	23.5
Aperture assembly	2.2
Gate valve and external plumbing	10.9
Sensors and harness	3.0
Support straps	6.1
Plumbing (internal)	8.0
Helium insert	43.6
External support structure	25.5
Solid Neon	172.8
Total	**395.6 kg**

Table 2 XRS Cryostat Mass Properties



EXTERNAL VIEW



SECTIONAL VIEW

Figure 1 The XRS Cryostat.

2.0 Constellation-X: The micro-calorimeter of the Spectroscopy X-Ray Telescope (SXT) on Constellation-X will observe in the same 0.3 keV to 10 keV energy band as XRS but with a six-fold increase in energy resolution. At present, several detector technologies are being developed for use on Constellation-X. One is the super-conducting Transition Edge Sensor (TES) system and the other is the Neutron-Transmutation-Doped semiconductor (NTD) based system.

Each detector array requires cooling, which will be provided by an adiabatic demagnetization refrigerator (ADR), to temperatures below 100 mK. Cooling requirements for the ADR will depend on two factors. The first is which of the competing detector technologies will be chosen for Con-X, since they differ in the amount of dissipated power at the ADR's operating temperature and also at higher temperature nodes. The more important factor, however, is the type of cryogenic system used as a heat sink for the ADR. The possibilities, which include superfluid helium, solid hydrogen, and mechanical cryocoolers, differ markedly in terms of the temperature and cooling power they can provide. The optimal size and configuration of the ADR may be quite different for each combination of detector and cooler options.

The current approach is to develop an ADR whose cooling capabilities are compatible with the worst case scenario (high detector cooling power and high heat sink temperature). In this case, conventional single-stage, single-shot ADRs, as on XRS, are unsuitable since they would be unmanageably large for high duty cycle observations. The better option is the multi-stage continuous ADR (CADR). Present design goals for the CADR are continuous cooling at temperatures as low as 50 mK, cooling power as high as 10 μW, and a heat sink temperature in the range of 6-10 K. This will envelop the requirements for all detector technologies and acceptable cryocooler options.

In what follows, consideration is given only to the TES detector system. This is not a choice between technologies but a choice of starting point. Configurations built around an NTD detector system will be considered in the near future.

2.1 Thermal Loads: A schematic of a cryostat and TES calorimeter is shown in Figure 2 where heat loads on an ADR and cryocooler are given. The heat loads on the ADR are used in subsequent scaling whereas the loads from warmer parts are those expected in a cryocooler option only. Parasitic heat flows for the other options are scaled separately. It is assumed that advancements in design and construction will reduce parasitic loads beyond the XRS standard, beyond what can be accounted for by the reduction of the main shell temperature.

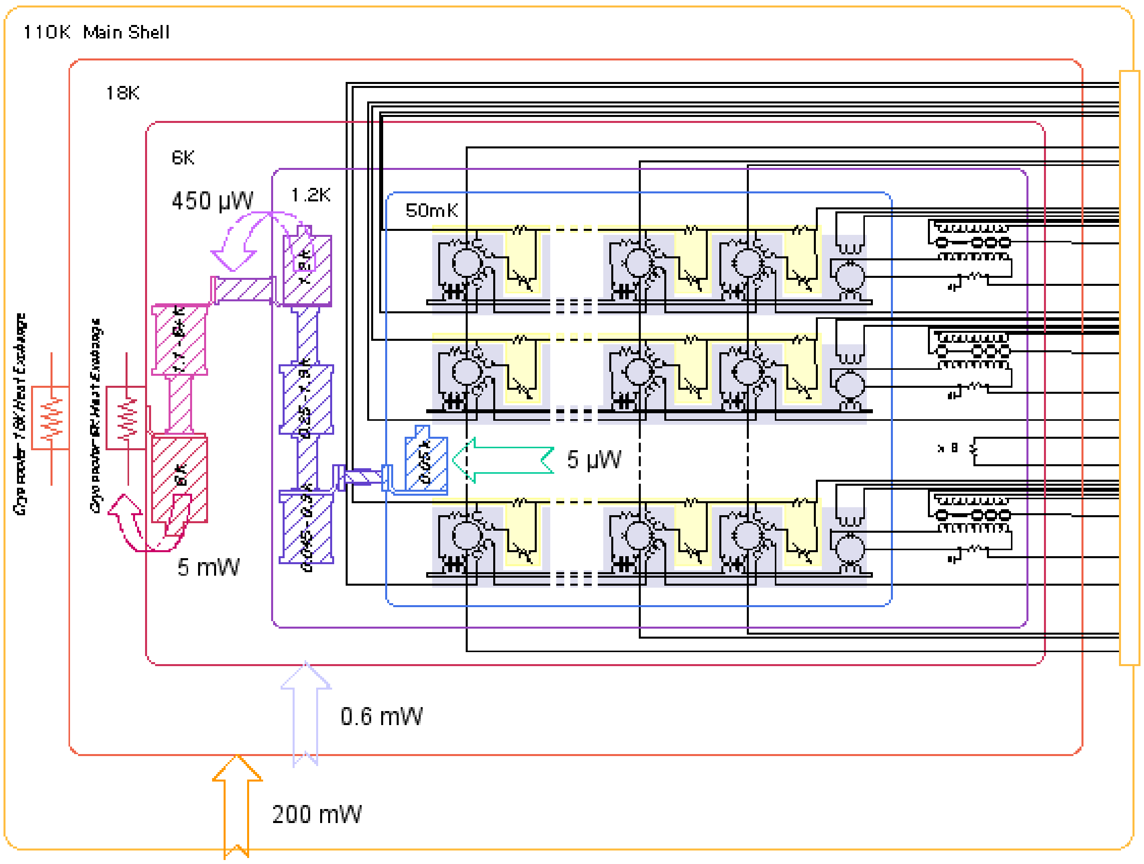


Figure 2 Calorimeter schematic and representative heat flow.

The 450 μW load on the 1.2 K stage, superfluid helium or an upper ADR stage, includes 360 μW from the ADR, 32 μW from the so called series array (SQUID amplifiers), with other parasitics accounting for the remainder.

2.2 Scaling Methodology: XRS heat maps provided an excellent starting point from which to scale heat flows for the three stored cryogen options considered here. Major components of the overall heat flow were segmented in a hierarchy determined mostly by geometrical connections and appropriate scaling laws were applied to each segment. No complete nodal analysis was attempted. All scaling calculations were carried out with routines developed in *Mathematica* and based on a main shell temperature of 110 K. Scaled temperature distributions of the shields, between the main shell and the guard cryogen, are given in Figure 3 for various exterior thermal conditions.

Radiation loads were scaled for T^4 as well as surface area dependence. This required a few manual iterations, for surface area calculations, between *Mathematica* and a 2D CAD application where the design was carried out (see Figure 4). A Lockheed MLI conductance model was used to scale MLI conductance/radiation loads and a $T^{2.3}$ dependence was used for all other conductive parasitics. The $T^{2.3}$ dependence was determined from thermal-conductivity-integral data for a number of common conductors used in stored cryogen systems. The loads during a proposed Delta launch are, at worst, 1/6 that of the M-5 for Astro-E. Assuming a proportionate reduction in cross sectional area, conductances of support straps and struts were further scaled by the same 1/6.

All options include recent continuous multi-stage ADR developments through the first three stages. Cryogen volumes were designed for a 6 year lifetime (5 years of joint operations plus one year between launches) at 95% fill fraction. The magnetic/mechanical cooling option (Option 3) is immune from this lifetime limitation. The optical path length inside the cryostat is limited by its geometry in relation to the maximum main-shell filter diameter, i.e., a 2.5” diameter filter set along a cone with base diameter of 1.6 meters and a height of 10 meters.

No specific margins were applied at any step in the scaling – all calculations are based on best current estimates of relevant parameters.

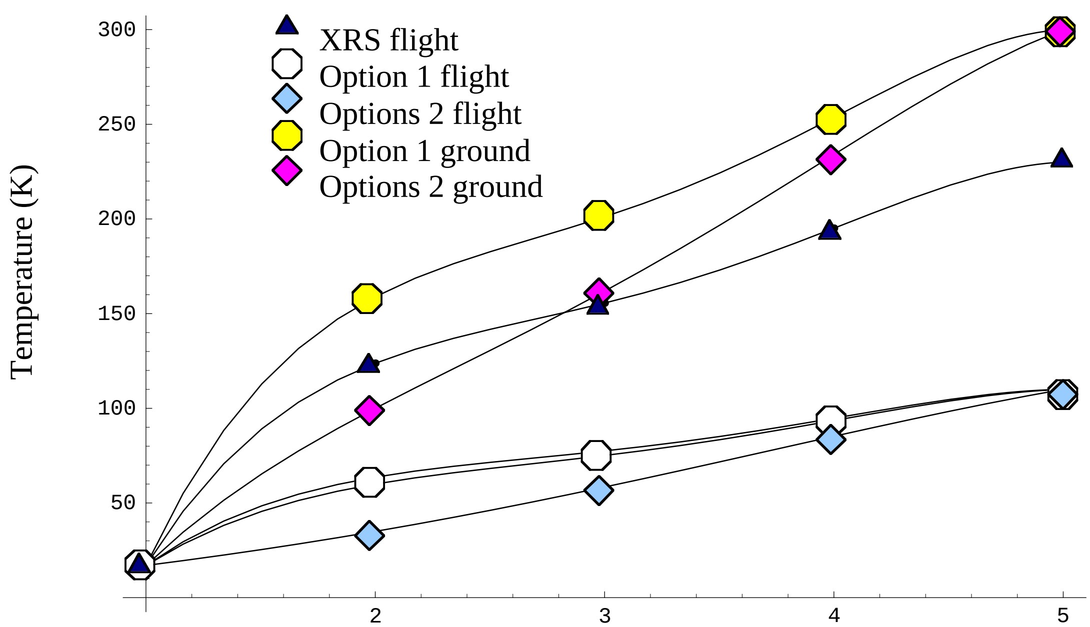


Figure 3 Scaled temperature distribution of the shields between the main shell (right) and the guard cryogen (left). The abscissa scale is arbitrary - values represent relative positions of the shields.

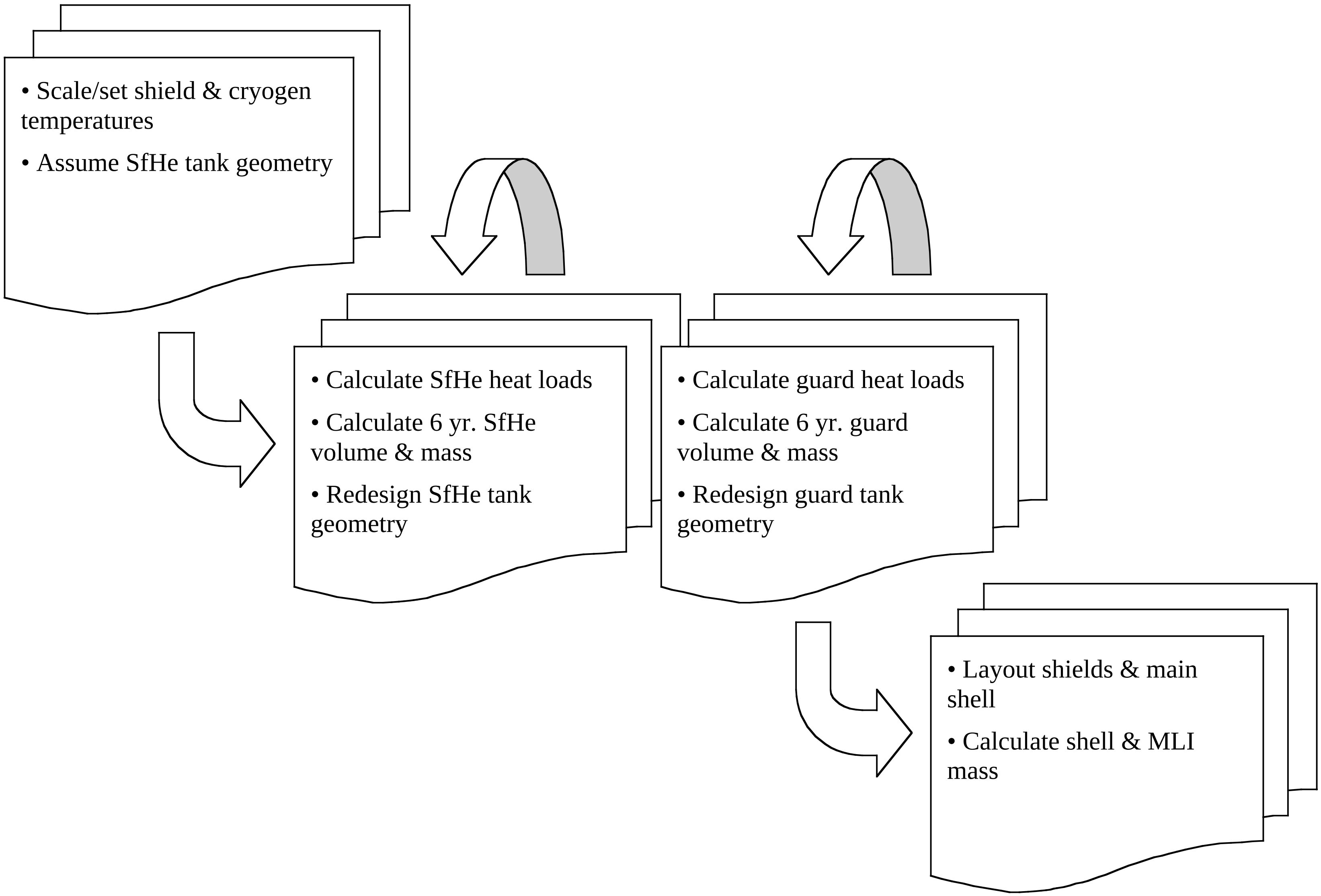


Figure 4 Flow chart of the scaling process for Options 1, 2a and 2b..

2.3 Cryostat Options: There are many combinations and permutations of cryogens and mechanical cryocoolers that might be configured to meet the cooling needs of Constellation-X. Some of those are shown in the outline below. The four chosen for further study bracket the possibilities: a dual stage stored cryogen plus ADR system (Option 1) most closely related to that of XRS; two hybrid cryogen-cryocooler plus ADR systems – one with a solid neon (SNe) guard (Option 2a) and the other with a solid hydrogen (SH_2) guard (Option 2b); and a cryocooler only plus ADR system (Option 3) which has been the Constellation -X baseline for some time. No system was considered that used SH_2 as the primary cryogen, since the gap between 1.3 K and 6-7 K would need to be bridged by a riskier warmer ADR stage.

Results of the scaling are described in the subsections below. Mass summaries are given in tabular form and designs are given both in a rendering of the exterior and in cross-section showing some internal details. The corresponding graphics for the different options are of equal scale respectively and can be compared for relative size.

Outline of Available Cooling Options

Stored Cryogen + ADR System
- **Single Stage**
  - SfHe (vapor cooling at several intermediate temperatures for filters)
  - SH_2 (little vapor cooling available)
- **Dual Stage**
  - SfHe Primary with SH_2/SNe Secondary (Guard) (vapor cooling from He & Ne)
  - SH_2 Primary with SH_2/SNe Secondary (Guard) (vapor cooling from Ne)

Hybrid Cryogen-Cryocooler + ADR System
- **Cryocooler guard for single stage cryogen** (Flight and/or Ground)
  - SfHe (vapor cooling at several intermediate temperatures for filters)
  - SH_2 (little vapor cooling available)
- **Cryocooler guard for secondary cryogen of dual system** (Flight and/or Ground)
  - SfHe Primary with SH_2/SNe Secondary (Guard) (vapor cooling from He & Ne)
  - SH_2 Primary with SH_2/SNe Secondary (Guard) (vapor cooling from Ne)

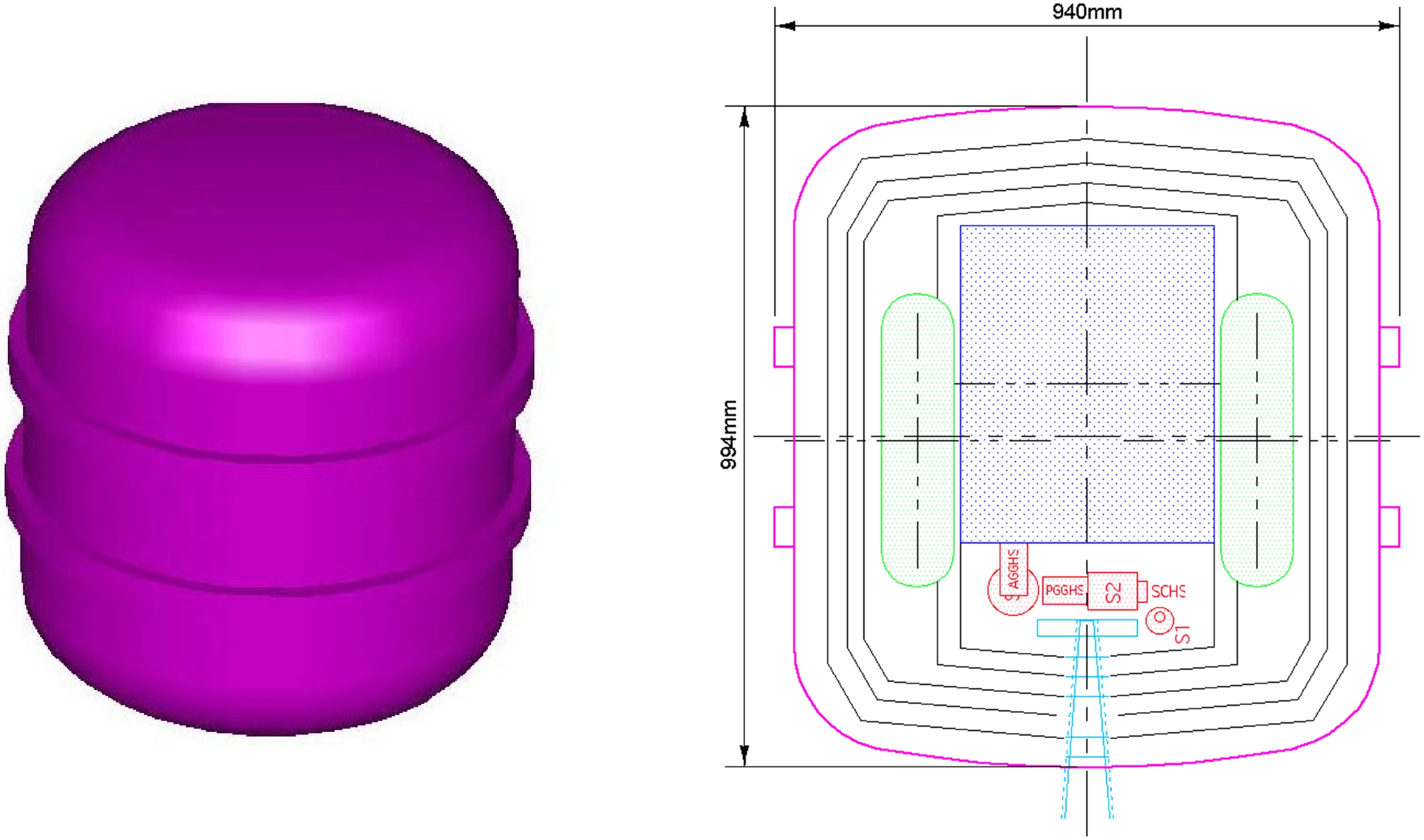
Cryocooler + ADR System
- **Radiative Precooling**
  - Required/desirable for all cryocoolers
- **No Radiative Precooling**
  - May require mechanical precooling or multiple stages

2.3.1 Cryostat Option 1: Cryostat Option 1 is the most direct scaling from the XRS system and consists of a three stage continuous ADR heat sunk to a 1.2 K superfluid helium reservoir. All that then guarded by a ~17 K solid neon cooled shield.

Mass properties are presented in Table 3 and the design is laid out in Figure 5.

Element	Mass (kg)
Cryostat main shell	59.6
Neon tank and shroud	27.2
Vapor cooled shields and MLI	20.5
Aperture assembly	2.5
Gate valve and external plumbing	11.0
Sensors and harness	3.0
Support straps	2.0
Plumbing (internal)	8.0
Helium tank and shroud	11.4
Liquid Helium	5.9
Solid Neon	63.4
Subtotal	**214.5**
External support structure	10.0
ADR	2.0
Front End Assembly	2.0
Total	**228.5 kg**

Table 3 Cryostat Option 1 Mass Properties



EXTERNAL VIEW SECTIONAL VIEW

Figure 5 Layout of Cryostat Option 1: : Main Shell (purple); 3-stage advanced ADR (red); Focal Plane Assembly & Optical Path (lt. blue); Superfluid Helium tank (dk. Blue); Solid Neon tank (green).

2.3.2 Cryostat Option 2a: Cryostat Option 2a consists of the three stage CADR thermally connected to a 1.2 K superfluid helium reservoir. All that then guarded by a ~15 K solid neon cooled shield. The goal here was to investigate the effect of a 35 K mechanically cooled inner shield (MCIS) on the cryogen system of Option 1. It is assumed, but expected, that with the colder MCIS, a 15 K neon guard is achievable.

Mass properties are presented in Table 4 and the design is laid out in Figure 7. A plot of mass vs lifetime (Figure 6) shows a one-year lifetime mass of 97 kg - barely under the current mass limit. One could consider this the zero-lifetime mass for joint operations.

Element	**2 yr Mass (kg)**	**4 yr Mass (kg)**	**6 yr Mass (kg)**
Cryostat main shell	22.8	29.5	35.6
Neon tank and shroud	18.8	22.6	27.5
Vapor cooled shields and MLI	9.1	11.6	14.2
Aperture assembly	2.5	2.5	2.5
Gate valve and external plumbing	11.0	11.0	11.0
Sensors and harness	3.0	3.0	3.0
Support straps	2.0	2.0	2.0
Plumbing (internal)	6.0	7.0	8.0
Helium tank and shroud	6.9	8.8	10.4
Liquid Helium	1.6	3.2	4.9
Solid Neon	8.1	11.5	19.9
Cryocooler	4.0	4.0	4.0
Subtotal	**95.8**	**116.7**	**143.0**
External support structure	6.0	7.0	8.0
ADR	2.0	2.0	2.0
Front End Assembly	2.0	2.0	2.0
Total	**105.8 kg**	**127.7 kg**	**155.0 kg**

Table 4 Cryostat Option 2a Mass Properties

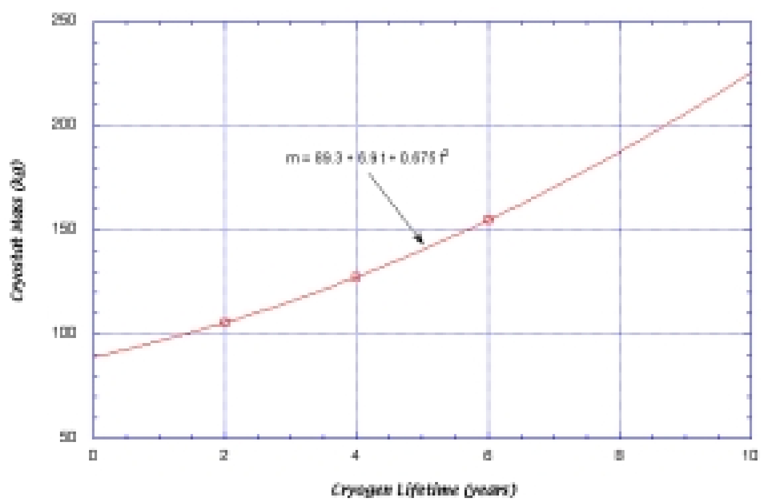
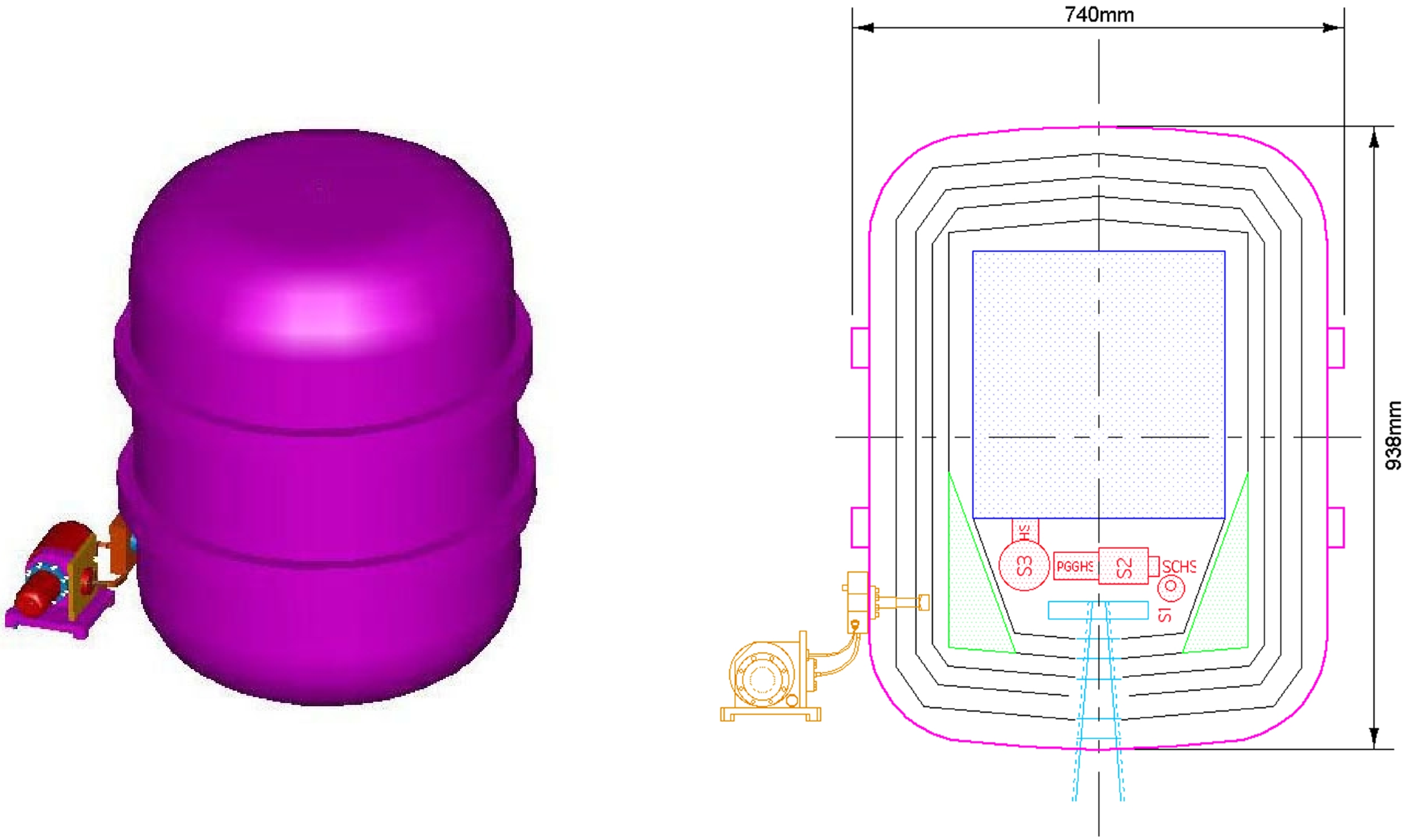


Figure 6 Plot of total cryostat mass vs. cryogen lifetime for Option 2a.



EXTERNAL VIEW SECTIONAL VIEW

Figure 7 Layout of 6 year Cryostat Option 2a : Main Shell (purple); 3-stage advanced ADR (red); Focal Plane Assembly & Optical Path (lt. blue); Superfluid Helium tank (dk. Blue); Solid Neon tank (green); 35 K Pulse Tube cryocooler (lt. brown).

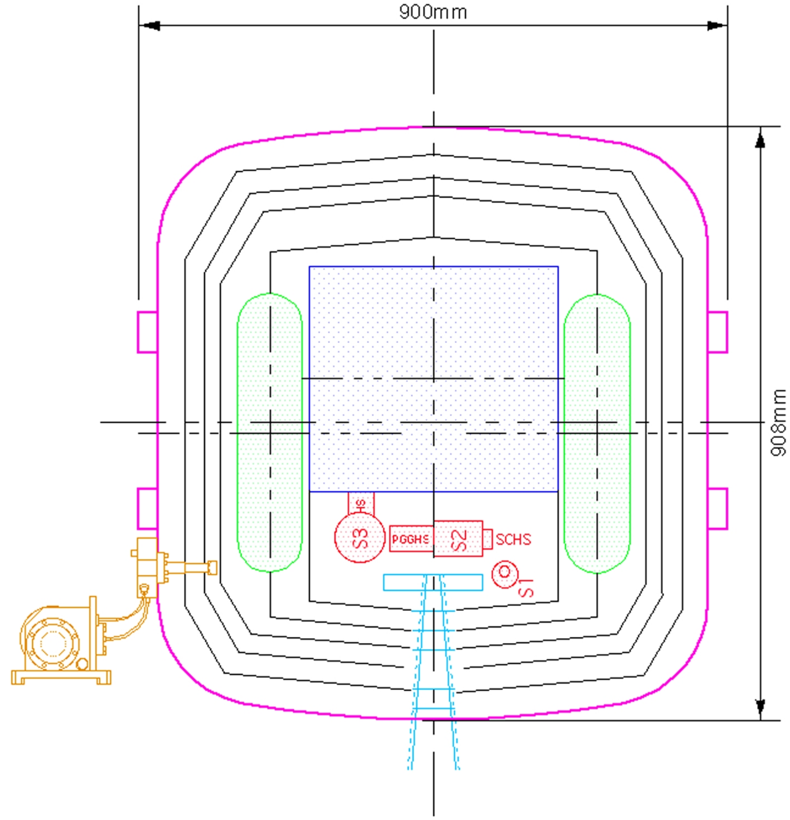
2.3.3 Cryostat Option 2b: Cryostat Option 2b is a variant of Option 2a with ~12 K solid hydrogen substituted for the solid neon. The goal here was to determine whether there were any mass gains over Option 2a. It is assumed, but expected, that with the colder MCS, a 12 K hydrogen guard is achievable.

Mass properties are presented in Table 5 and the design is laid out in Figure 8.

Element	Mass (kg)
Cryostat main shell	47.2
Hydrogen tank and shroud	25.2
Vapor cooled shields and MLI	15.9
Aperture assembly	2.5
Gate valve and external plumbing	11.0
Sensors and harness	3.0
Support straps	2.0
Plumbing (internal)	8.0
Helium tank and shroud	9.7
Liquid Helium	4.2
Solid Hydrogen	5.3
Cryocooler	4.0
Subtotal	**138.0**
External support structure	8.0
ADR	2.0
Front End Assembly	2.0
Total	**150.0 kg**

Table 5 Cryostat Option 2b Mass Properties

EXTERNAL VIEW



SECTIONAL VIEW

Figure 8 Layout of Cryostat Option 2b : Main Shell (purple); 3-stage advanced ADR (red); Focal Plane Assembly & Optical Path (lt. blue); Superfluid Helium tank (dk. Blue); Solid Hydrogen tank (green); 35 K Pulse Tube cryocooler (lt. brown).

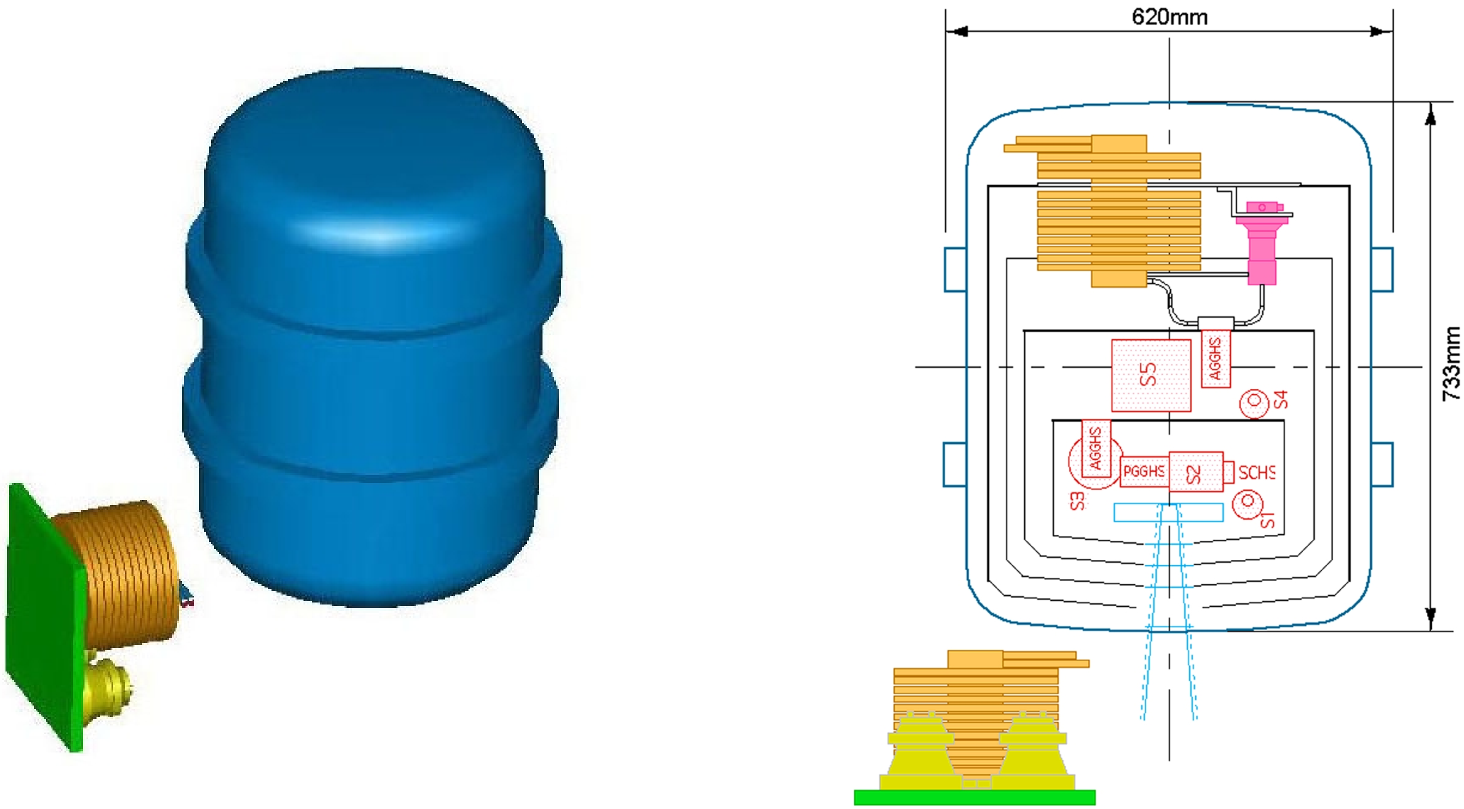
2.3.4 Cryostat Option 3: Cryostat Option 3 is the baseline mechanical/magnetic cooling configuration. It incorporates an additional stage on the ADR to reach the 6+ K interface temperature with the cryocooler as well as a continuous stage at the 1.2 K shield. The 1.2 K temperature is used here to coincide with the SfHe temperarture of the other cryostat options. The final design temperature for this continuous stage will be fixed at some value less than 2 K, to provide thermal stability to a filter and the series array squids as well as optimal, lowest magnetic field, design of the final ADR stage.

Strictly speaking this was a packaging effort and not a scaling problem. The same envelope was used for the coldest stages of the ADR as was used in the other cryostat options. An enveloping 6+ K structure and shroud was constructed to house the expected bounds of a final ADR stage. An existing developmental design of a turbo-Brayton cryocooler was split, with the colder components being placed inside the main vacuum shell and the warmer components being mounted to a radiator on the side of the spacecraft. Two radiation shields are connected to the cold recuperator inside the cryostat and are, in a sense, actively cooled, where the combination will float near targeted temperature ranges. The “warm” bearings of the turboalternator are heat sunk to the outer shield at a temperature expected to be in the 60-80 K range. The colder 6+ K end of the turboalternator protrudes inside the inner 18± K shield for the radiation protection it would afford. A heat exchanger at the cold end of the cryocooler flow loop is connected to the 6+ K structure and shroud to heat sink the ADR. Cryocooler dimensions are based on existing component prototypes.

Mass properties are presented in Table 6 and the design is laid out in Figure 9.

Element	Mass (kg)
Cryostat main shell	30.5
Shields and MLI	14.8
Aperture assembly	2.5
Gate valve	4.0
Sensors and harness	3.0
Support straps	2.0
Cryocooler (internal)	10.0
Subtotal	**66.8**
Cryocooler (external)	18.0
External support structure	8.0
ADR	4.0
Front End Assembly	2.0
Total	**98.8 kg**

Table 6 Cryostat Option 3 Mass Properties



EXTERNAL VIEW

SECTIONAL VIEW

Figure 9 Layout of Cryostat Option 3: Main Shell (blue); multistage advanced CADR (red); Focal Plane Assembly & Optical Path (lt. blue); turbo-alternator (pink); recuperator (lt. brown); compressors (yellow). The plumbing connecting the internal and external components is not shown.

3.0 Discussion: Again, the effort reported here was an attempt to identify a cooling solution with less technological risk that would also fall within the current mass and volume constraints. We began by scaling directly the XRS system for the colder Constellation-X environment (Option 1). We then modified that design by incorporating an off-the-shelf 35 K pulse tube cryocooler to actively cool an inner shield surrounding the guard shield (Options 2a & 2b). Finally, we developed a configuration for the baseline cryocooler solution (Option 3).

Shown in Figure 10 is the Option 3 cryostat and external cryocooler components (attached to a side radiator panel) incorporated into the current spacecraft model.

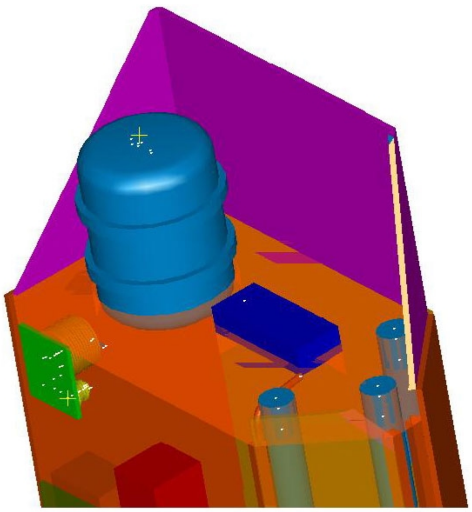


Figure 10 Rendering of Cryostat Option 3 placed on the bench of the current space craft configuration. The bench is semi-transparent.

The cryostat of Option 1 has proven to be far too large and massive to be considered. The cryostat of Option 2b gets closer to the mass allocation, but is still too large to fit on the detector bench. A mass trade between Options 2a and 2b is a wash, so the more hazardous hydrogen should be avoided in favor of Option 2a, which does just fit within the sunshade envelope. A reduced mission life does not bring even Option 2a within the cryostat mass budget of 100 kg. A reduction in the 110 K main shell temperature will not help enough with Option 1 and will have little affect on the mass of the hybrid cryostats of Options 2. The cryocooler configuration of Option 3 remains the only option to meet both mass and volume constraints.

The next step in this process is to do a more detailed design of the external support structure so that it and the main shell can be incorporated into the space craft thermal model. From that, more accurate determination can be made of the main shell temperature and that then iterated into the above designs. It is expected that the designs of any option could only get better, so in that sense, there may actually be angels in the details.